

BOND PROBLEMS CAUSED BY THERMAL EXCURSION

By

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ABSTRACT

The failure mode caused by thermal deformation and thermal deformation effects on bond integrity are discussed herein. Thermocompression (TC) wedge bonding, ultrasonic bonding, and thermocompression ball (nailhead) bonding in small-signal transistors are considered. Repeated switching of these devices between high and low power at a rate that allows thermal expansion and contraction in the interconnecting wire causes the wire to flex at the point of reduced cross-sectional area until breakage finally occurs because of metal fatigue. This thermal deformation is related to many factors such as device power dissipation, current density in the wire, wire dress and length, the thermal time constant, and frequency of operation.

SUMMARY

The failure modes and mechanisms discussed in this paper are presented to familiarize reliability and design engineers with fatigue failures that occur in 2.54×10^{-5} m (1 mil) aluminum lead wire of small-signal transistors when subjected to thermal excursions. In April 1969, during testing prior to hot firing of a J-2 engine at the Rocketdyne engine test stand, a screened 2N2222A transistor failed open between the base and emitter in the Electrical Control Assembly (ECA) Ignition Phase Timer. The failed transistor was decapped by the manufacturer, and visual inspection revealed that the base lead wire had fractured at the heel of the thermal compression wedge bond to the semiconductor chip. Many 2N2222A and other small-signal transistors with 2.54×10^{-5} m (1 mil) aluminum wire are used by MSFC; therefore, the Quality and Reliability Assurance Laboratory decided to investigate this problem further. A study of the problem, its causes, extent, and the possible screening tests and inspections was conducted. It was known from previous studies that abrupt changes in the cross section of the wire because of the bonding

operation can cause a significant reduction in the wire fatigue strength. Such a change in cross-sectional area can be found at the heel of a 2.54×10^{-5} m (1 mil) aluminum ultrasonic or TC wedge bond or at the neck of a gold ball bond (nailhead), and metal fatigue caused by thermal deformation usually breaks the wire at this, the weakest, point.

To verify the existence of several factors that might affect thermal deformation, thermal analyses at various power cycling conditions were conducted on actual devices (Fig. 1). Analyses with the Scanning Electron Microscope (SEM) were also performed. The effects of wire dress were investigated and bond pulling tests were performed on some of the devices that survived power cycling tests.

POWER CYCLING TESTS

Since the failures to be investigated were mechanical in nature, namely cracking and separation of the bond wire at the heel of the bond, it was believed that accelerated stress testing such as by power cycling was the best approach for evaluating bond integrity and for duplicating the failure mode and mechanism of the failed transistor. To establish the extent to which thermal deformation caused by the temperature differential (ΔT) in the systems produces motion of the aluminum interconnecting wire, power cycling tests were conducted at various combinations of power level, current, and cycling time.

Parallel tests were conducted by MSFC and Manufacturer A. At the request of MSFC, Manufacturer A began power cycling tests at various operating conditions on devices using 0.0025 cm (0.001 in.) diameter aluminum interconnecting lead wire and TC wedge bonds, while MSFC began power cycling tests on devices using 0.0025 cm (0.001 in.) diameter ultrasonically bonded aluminum wire and devices using 0.0018 to 0.0025 cm (0.0007 to 0.001 in.) diameter gold TC bonds (wedge and nailhead).

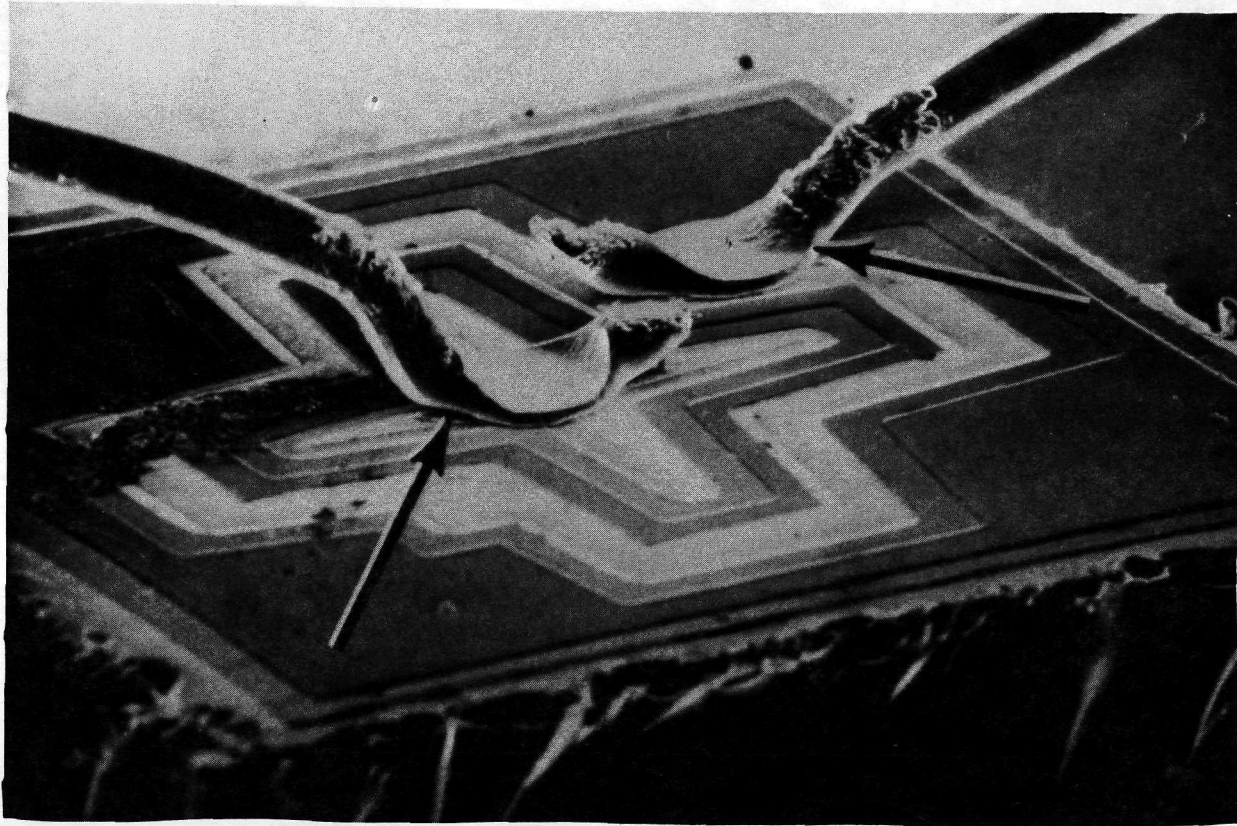


Figure 1. Manufacturer A transistor 2N2222A from ECA Ignition Phase Timer, typical TC wedge bond (220X magnification).

The common base configuration circuit shown in Figure 2 was used by MSFC. Each lead was inserted through five ferrite beads and attached directly at each transistor socket pin to minimize the occurrence of high frequency oscillations. The dc power was applied to each transistor by a common triple-pole contactor. At the end of the "on" cycle the contactor opened, simultaneously removing the dc power from the emitter, base, and collector.

The results of the tests performed by Manufacturer A on devices built with 2.54×10^{-5} (1 mil) TC wedge bonded aluminum lead wire are summarized in Table 1. The results of the tests performed by MSFC are summarized in Tables 2, 3, and 4. Table 2 summarizes the results of tests on devices manufactured by Manufacturers A and B, built with 2.54×10^{-5} m (1 mil) ultrasonically bonded aluminum lead wire and power cycled at maximum device-rated power. Table 3 summarizes the results of tests on devices from Manufacturer B, built with 2.54×10^{-5} m (1 mil) ultrasonically bonded

aluminum lead wire and power cycled under derated conditions. A cycling time of 1 min on and 1 min off was used, since thermal equilibrium on the TO-18 package under derated conditions can be reached in less than 1 min. Table 4 summarizes the results on devices manufactured by Manufacturers C, D, and E, built with 1.78×10^{-5} to 2.54×10^{-5} m (0.7 to 1 mil) TC bonded gold lead wire and power cycled at maximum device-rated power.

A plot of cumulative percent of failures versus cycles for devices operated under the same power current and repetition rates is shown in Figure 3. The data for the Manufacturer A 2N2222A (aluminum) TC bonds were not well correlated; therefore, the least squares method was used to determine the slope of the curve. Although the Manufacturer B ultrasonic bonds did not fail as early as the Manufacturer A TC bonds, the rate of failure of the Manufacturer B ultrasonic bonds after the initial failure is about the same as that experienced by the Manufacturer A TC bonds. This is illustrated by the fact that the two plots are nearly parallel.

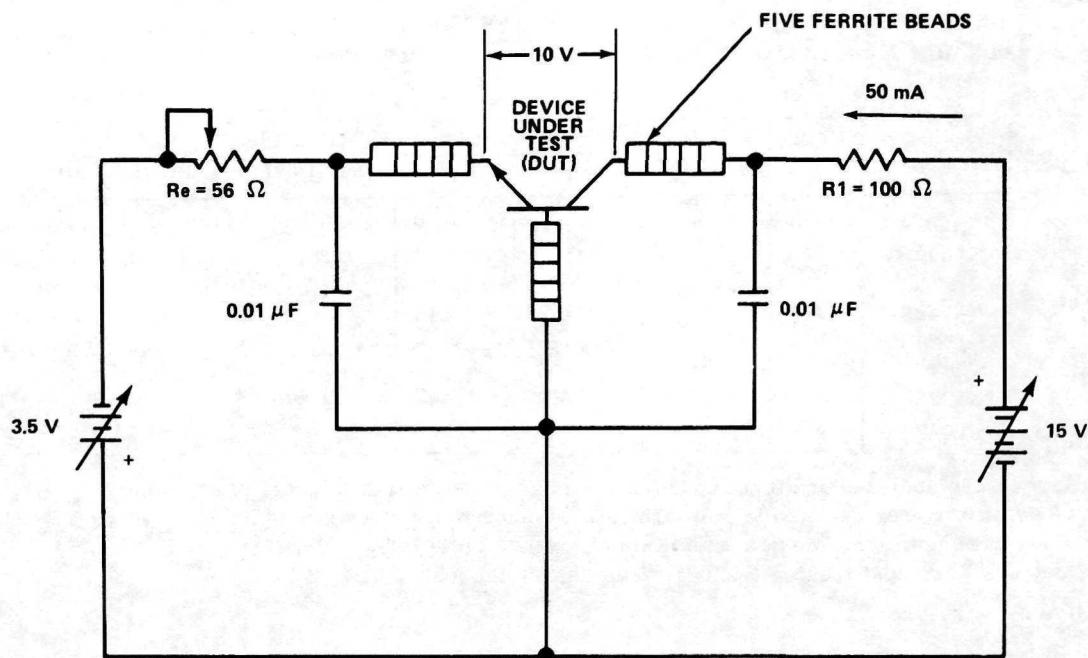


Figure 2. Power cycling test circuit.

TABLE 1. SUMMARY OF POWER CYCLING TESTS PERFORMED BY MANUFACTURER A ON THEIR OWN ALUMINUM THERMOCOMPRESSION WEDGE BONDS

Device Type	Date Code	Quantity	Test Conditions		Total Cycles Per Device ^a	Total Failures ^b
			P_D	I_C		
JAN2N2222A	6927A	85	500 mW	16.5 mA	8 058	13, First Occurred 2 at 2082 Cycles
JAN2N2222A	6927A	247	500 mW	50.0 mA	11 440	52, First Occurred 5 at 1600 Cycles
JAN2N2222A	6927A	750	165 mW	50.0 mA	23 640	38, First Occurred 10 at 1600 Cycles
JAN2N2222A	6927A	500	335 mW	50.0 mA	22 960	39, First Occurred 10 at 1600 Cycles
JAN2N2222A	6927A	500	165 mW	16.5 mA	21 902	3, First Occurred 1 at 588 Cycles
JAN2N2222A	6927A	500	335 mW	16.5 mA	22 630	43, First Occurred 4 at 588 Cycles

- a. Prior to 588 cycles the devices were power cycled at a rate of 5 min on and 5 min off, and thereafter at a rate of 3 min on and 3 min off.
- b. All failures were analyzed and found to be an open or broken lead at the heel of a semi-conductor bond.

TABLE 2. SUMMARY OF POWER CYCLING TESTS PERFORMED BY MSFC ON ALUMINUM ULTRASONIC BONDS (MAXIMUM DEVICE-RATED POWER)

Manufacturer	Device Type	Date Code	Quantity	Test Conditions		Total Cycles Per Device	Total Failures ^a
				P _D	I _C		
A	2N2222A (Group 1)	7040	100	500 mW	50 mA ^b	45 720	23, First Occurred 1 at 11 520 Cycles
B	2N2222A (Group 2)	6949	29	500 mW	50 mA ^c	61 320	21, First Occurred 1 at 8190 Cycles
B	2N2222A (Group 3)	7007	25 ^d	500 mW	50 mA ^c	44 570	18, First Occurred 1 at 18 410 Cycles

- All failures were analyzed and found to be an open or broken lead at the heel of a bond.
- All devices were power cycled at a rate of 2 min on and 2 min off.
- All devices were power cycled at a rate of 3 min on and 3 min off.
- These devices were heat treated (baked) by the manufacturer.

TABLE 3. SUMMARY OF POWER CYCLING TESTS PERFORMED BY MSFC ON ALUMINUM ULTRASONIC BONDS (DERATED CONDITIONS)

Manufacturer	Device Type	Date Code	Quantity	Test Conditions		Total Cycles Per Device	Total Failures ^a
				P _D	I _C		
B	2N2222A (Group 4)	7007	25 ^b	100 mW	50 mA ^c	135 660	1 at 83 070 Cycles
B	2N2222A (Group 5)	7007	25 ^b	25 mW	10 mA ^c	138 660	0
B	2N2222A (Group 6)	7007	25 ^b	20 mW	10 mA ^{c,d}	135 660	0

- All failures were analyzed and found to be an open or broken lead at the heel of a bond.
- These devices were heat treated (baked) by the manufacturer.
- All devices were power cycled at a rate of 1 min on and 1 min off.
- Devices were in a steady-state environmental condition of $85 \pm 3^\circ\text{C}$ during both the on and off power cycling.

The effects of lead dressing were studied also. It was noted that post-to-die leads that are dressed straight are more prone to fail than leads that are provided with a loop of the proper height [17.78×10^{-5} to 25.4×10^{-5} m (7 to 10 mil)] when subjected to a given number of stress cycles. The explanation seems to be that when a service loop is present, the expansion and contraction of the wire caused by temperature changes causes only a very small flexion of the wire in the region of the bond heel. Calculations made by the National Bureau of Standards have shown that the increase in loop height, and

therefore the amount the heel flexed, is inversely proportional to the height of the loop measured at room temperature (initial height).

SCANNING ELECTRON MICROSCOPE

The devices that failed during power cycling test were decapped and analyzed using the SEM. Examination of the failed bonds showed that the separation occurred at the heel of the bonds

TABLE 4. SUMMARY OF POWER CYCLING TESTS PERFORMED BY MSFC ON GOLD THERMOCOMPRESSION BONDS (MAXIMUM DEVICE-RATED POWER)

Manufacturer	Device Type	Date Code	Quantity	Test Conditions		Total Cycles Per Device ^a	Total Failures
				P _D	I _C		
C	2N2222A (Group 7)		19	500 mW	50 mA	50 320	0
D	JAN2N2222A (Group 8)		13	500 mW	50 mA	87 150	0
C	S2N910 (Group 9)	6750 6812 6815	49	500 mW	50 mA	72 120	0
E	S2N718 (Group 10)	6450 6520	49	500 mW	50 mA	72 930	1 at 42 060 Cycles
D	S2N718 (Group 10)	6948	49	500 mW	50 mA	72 930	1 at 19 880 Cycles

a. All devices were power cycled at a rate of 3 min on and 3 min off.

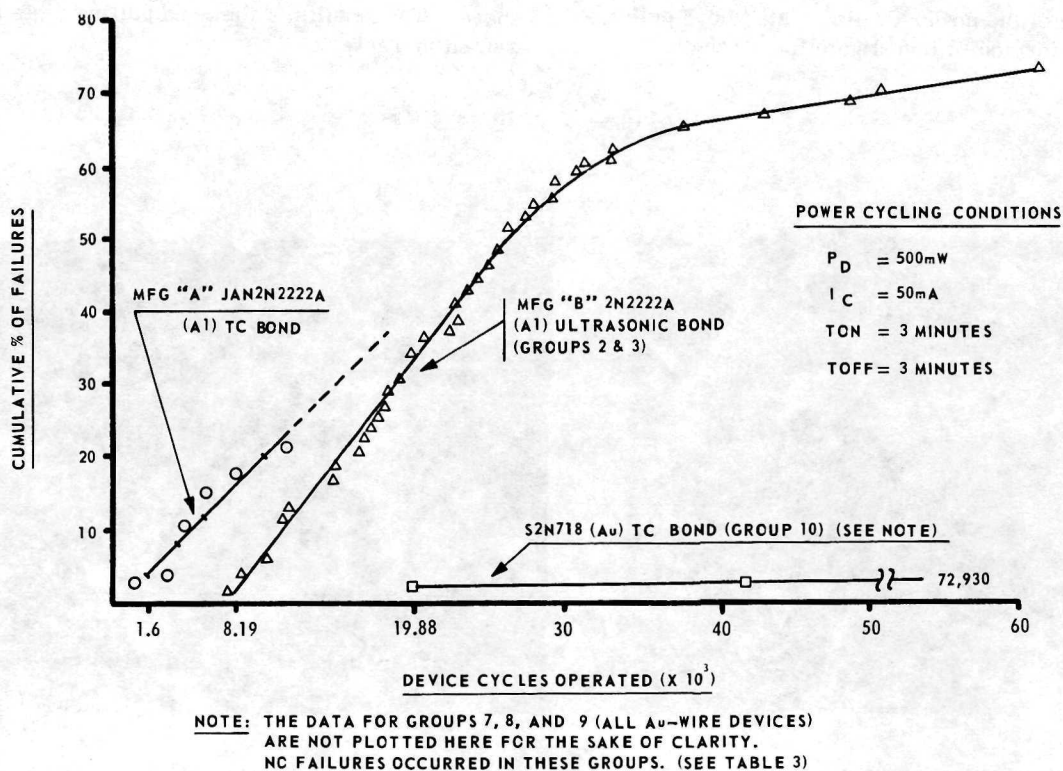


Figure 3. Percentage of failures.

(Figs. 4 and 5). The rough appearance of the wire in the areas of separation indicates a fatigue fracture mechanism. Also, to study the bond degradation during power cycling, a random sample of devices was taken from group 2, decapped, and analyzed using the SEM before and during power cycling and after failure. Figures 6, 7, and 8 depict clearly the increasing depth of the microcracks as a function of duration and severity of power cycling.

When examined with the SEM, electrically good devices from groups 4 and 5 that were power cycled under conditions (power, current, and repetition rates) less strenuous than the devices in groups 2 and 3 did not exhibit bond degradation at the heel even after 113 430 cycles. A sample of electrically good devices was taken from groups 2 and 3 after 41 650 cycles and analyzed using the SEM. It was found that these devices had deep microcracks at the heel of the bonds, such that the electrical continuity was about to be broken.

BOND PULLING TESTS

At the end of the power cycling tests, bond pull tests were performed to investigate the strength of

the 2.54×10^{-5} m (1 mil) diameter aluminum and 2.54×10^{-5} m (1 mil) diameter gold interconnecting lead wires. The pull tests were performed on all bonds of the devices that had undergone SEM analysis. The pull tests were performed using a Micro Bond Tester. A thin molybdenum wire hook was carefully positioned under the loop of the interconnecting lead wire about midway between the die bond and the post bond of the transistor mounted on a fixed stage. The hook was attached to a retained reading dynamometer that was motor-driven at a constant angular velocity to apply a uniform loading rate. The loading rate used to pull the 2.54×10^{-5} m (1 mil) wire was 0.2 g/sec.

The failure loads for 2.54×10^{-5} m (1 mil) aluminum lead wire in the TO-18 packages were found to be in the range of 3.0 to 4.0 g for leads that are ultrasonically bonded to a system consisting of aluminum metallization on the die and gold-plated Kovar package posts. The failure loads for 2.54×10^{-5} m (1 mil) gold lead wire in the TO-18 packages were found to be in the range of 4.5 to 5.5 g for leads that are TC bonded in the same metallization system as above. The results of the bond pulling tests are presented in Table 5.

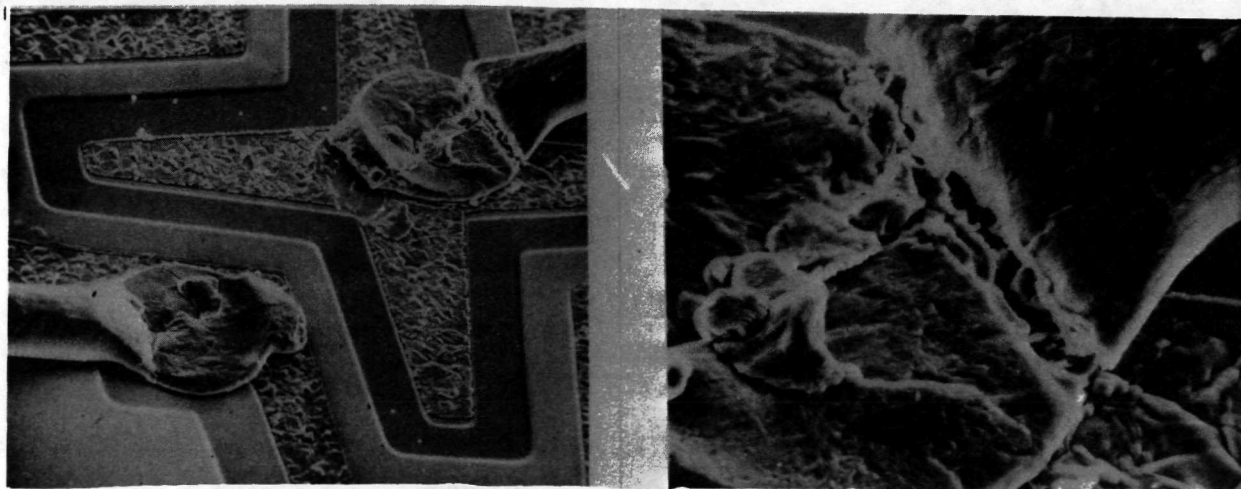


Figure 4. Manufacturer A transistor 2N2222A from ECA Ignition Phase Timer, TC wedge bond, emitter bond failed after 2240 power cycles.

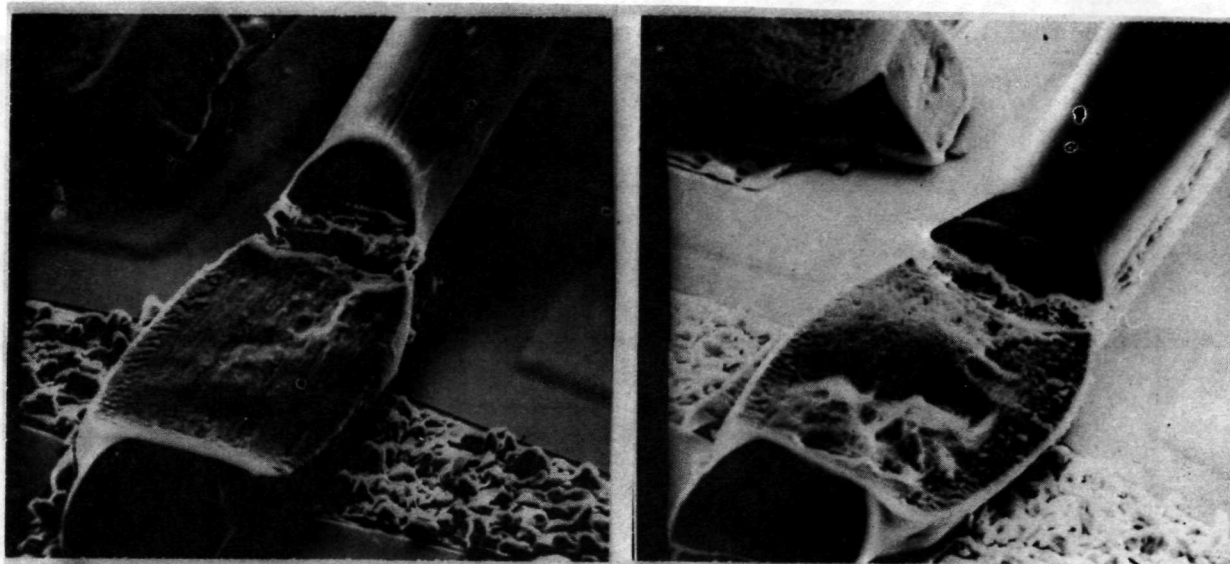


Figure 5. Manufacturer A transistor 2N2222A, group 1, die side bond, ultrasonic, open at heel.

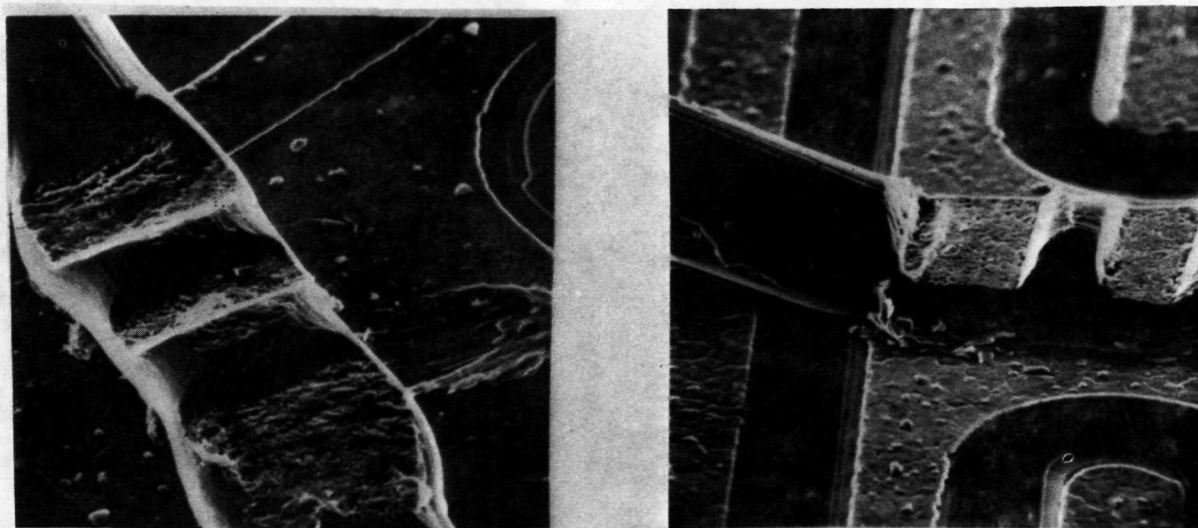


Figure 6. Manufacturer B transistor 2N2222A, serial number 75, die side bond, ultrasonic; evidence of microcracks at the heel before power cycling.

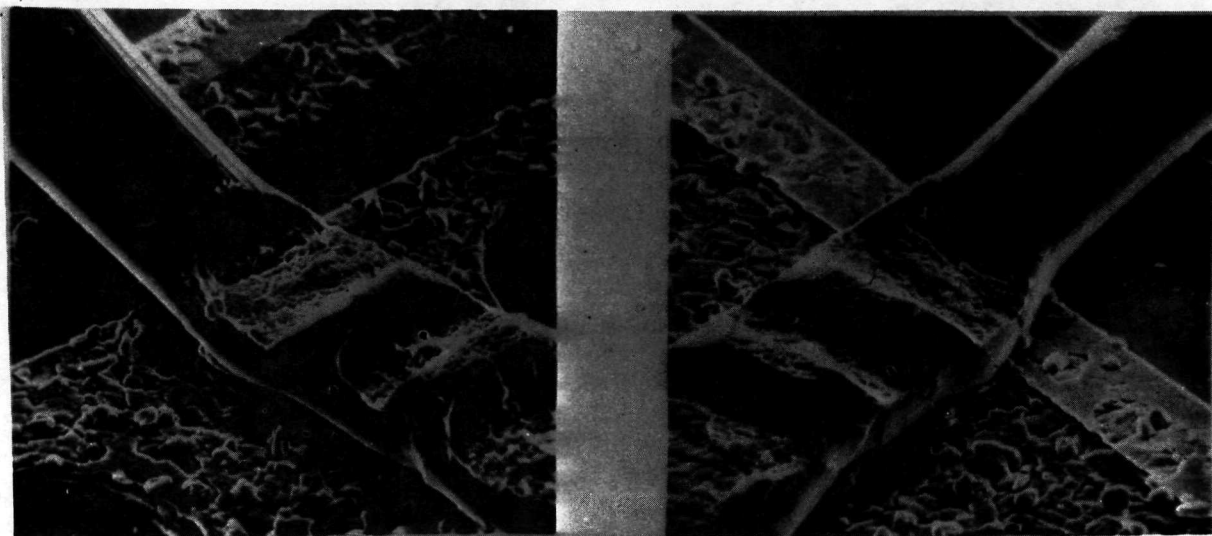


Figure 7. Manufacturer B transistor 2N2222A, serial number 75, die side bond, ultrasonic; microcrack depth increased after 3152 power cycles.

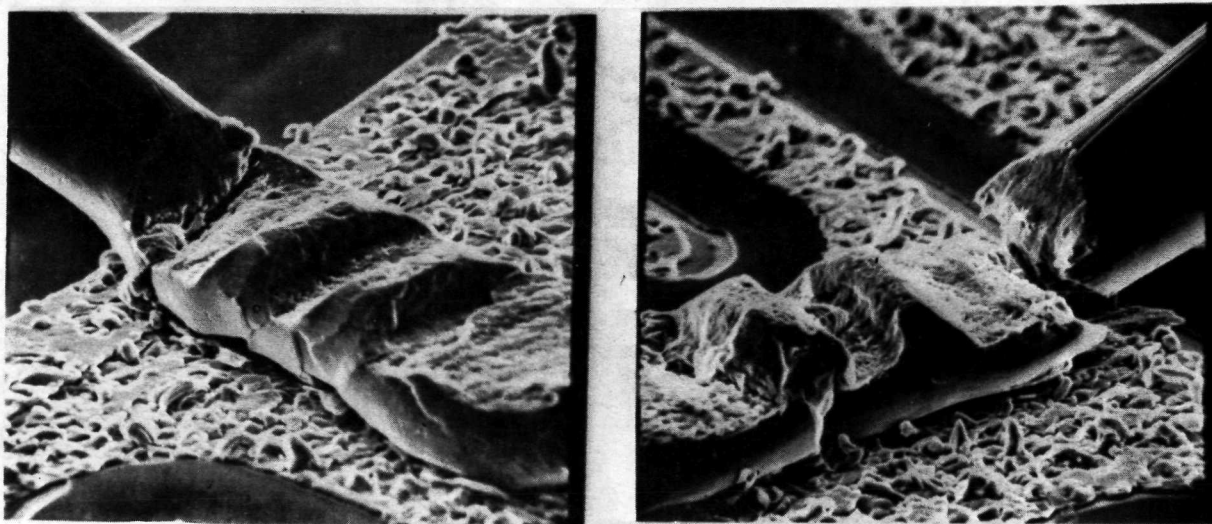


Figure 8. Manufacturer B transistor 2N2222A, serial number 75, die side bond, ultrasonic; open at heel after 14 500 power cycles.

TABLE 5. RESULTS OF BOND PULLING TESTS PERFORMED BY MSFC

Transistor	Manufacturer/ Group	Power Cycles	Devices Pulled	Average Force, g		Wire Type and Bond Type	Pull Test Remarks	
				Emitter	Base		Emitter	Base
JAN2N222A	D/8	80 430	2	5.5	5.0	Gold/TC	Wire Broke	Wire Broke
S2N910	C/9	64 730	2	5.5	5.0	Gold/TC	Wire Broke	Wire Broke
2N718A	E/10	68 880	2	8.0	8.0	Gold/TC	Bond Lifted (1) Bond Broke at Post (1)	Bond Broke at Heel (1) Bond Lifted at Heel (1)
2N718A	D/10	68 880	2	8.0	8.0	Gold/TC	Wire Broke	Wire Broke
2N2222A	B/3	44 570	5	1 to 2.5	0+ to 4	Aluminum/US	Bond Broke at Heel and Some at Post	Bond Broke at Heel and Some at Post
2N2222A	B/4	135 660	7	2.5 to 4	1 to 3.5	Aluminum/US	Bond Broke at Heel	Bond Broke at Heel and Some Lifted at Post

CONCLUSIONS

It was concluded that the thermal deformation was related to many factors such as device power dissipation, current density, wire dress and length, thermal time constants (system), and frequency of operation. Also, it was noted that the greater the temperature differential (ΔT) in the systems, the greater will be the motion of the interconnecting lead wire because of thermal deformation. Therefore, if significant microcracks or tool marks are present at the heel of the bonds and if the lead does not have an adequate loop height, thermocompression wedge bonds may fail as early as 1600 cycles, and ultrasonic bonds may fail as early as 8000 cycles. When examined under the SEM, devices power-cycled under derated conditions did not exhibit bond degradation at the heel, even after 100 000 cycles.

Devices using 2.54×10^{-5} m (1 mil) thermo-compression bonded gold lead wire withstood the same power cycling conditions much better than either TC or ultrasonically bonded aluminum wire.

Out of a total of 179 gold wire devices tested there were two failures, one at 19 880 cycles and another at 42 060 cycles. There was virtually no degradation in the gold wire bond strength as a result of power cycling.

According to the National Bureau of Standards, a loop of adequate height significantly improves reliability by reducing the amount of flexion caused at the heel of the bond when the temperature changes.

Devices using 2.54×10^{-5} m (1 mil) aluminum lead wire may be used safely in power cycling applications only if very close control of the bonding process is maintained to assure that tool marks, microcracks, or insufficient cross-sectional areas are not present on the heels of the bonds. An adequate loop must also be provided in the wire. The methods or degree of control necessary to prevent said conditions have not been determined, but a study is underway with a transistor manufacturer to develop some nondestructive screening procedures and to establish the controls necessary for the variables of the bonding process.

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